Results of an Internet-Based Dual-Frequency Global Differential GPS System

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Biography

Ronald Muellerschoen received a B.S. degree in physics at Rensselaer Polytechnic Institute and a M.S. degree in applied math at the University of Southern California. He is currently a Member of the Technical Staff in the Orbiter and Radio Metric Systems Group at the Jet Propulsion Laboratory (JPL). His work at JPL has concentrated on the development of filtering software for processing GPS data and development of wide area differential systems.

Willy Bertiger received his Ph.D. in Mathematics from the University of California, Berkeley, in 1976. In 1985, he began work at JPL as a Member of the Technical Staff in the Orbiter and Radio Metric Earth Systems Group. His work at JPL has been focused on the use of GPS, including high precision orbit determination, positioning, geodesy, remote sensing, and wide area differential systems.

Michael Lough obtained a Ph.D. in Applied Mathematics from the California Institute of Technology in 1995. Since 1997, he has worked in JPL's Orbiter and Radio Metric Systems Group. His current interests include the development of techniques for improving GPS-based precise orbit determination (POD) strategies for low-Earth orbiters as well as the development of real-time tools for GPS analysis.

Abstract

Observables from a global network of 18 GPS receivers are returned in real-time to JPL over the open Internet. 30-40 cm RSS global GPS orbits and precise dual-frequency GPS clocks are computed in real-time with JPL's Real-Time Gipsy (RTG) software. Corrections to the broadcast orbits and clocks are communicated to the user over the open Internet via a TCP server. Tests of user positioning show real-time RMS accuracy of 8 cms RMS in horizontal and 20 cms RMS in the vertical.

Introduction

The JPL architecture for a GPS global real-time differential system was first put forward by Tom Yunck et al. [*1995, 1996*]. A commercial North American Wide Area Differential GPS (WADGPS) system based on the JPL architecture and software was implemented in 1997 [*Whitehead et al. 1998; Bertiger et al. 1998*]. In 1996 the Federal Aviation Administration (FAA) selected the JPL architecture and software as a prototype for their Wide Area Augmentation System (WAAS). WAAS as well as all other existing differential systems are optimized for users with a single-frequency GPS receiver, which are susceptible to large, un-modeled ionospheric delays. In order to compensate for this error source, these differential systems employ a dense network of reference stations over their service area (for example, WAAS uses 24 reference stations over the continental US). Maps of the total electron content (TEC) must be transmitted to their single-frequency users. In contrast, a dual-frequency receiver does not need this information, hence greater accuracy is achievable, and fewer reference sites are needed. Furthermore, all existing differential systems are regional, in that they serve a portion of the Earth's surface. Many of NASA's projects are global in nature and demand the highest possible accuracy. The system discussed in this paper addresses the issues of accuracy and global coverage.

To address the issue of global coverage, we take advantage of NASA's Global GPS Network (GGN), which is operated and maintained by JPL. The GGN consists of approximately 50 sites which are mostly operated in batch mode over the Internet [http://igscb.jpl.nasa.gov]. To return data in real-time a new software set called Real-Time Net Transfer (RTNT) was developed. One Hz phase and range observables are returned over the open Internet using User Datagram Protocol (UDP). Better than 98% of the data is returned in less than 2 seconds. Currently 18 global sites are returning data in real-time to JPL. We expect to add several key additionally sites in the next few months. These new sites will increase the accuracy of the orbits and clocks, and also system reliability by having redundant receivers in the reference network.

To address the issue of accuracy, the system has been optimized for dual-frequency users. Both range and phase dual-frequency observables are used from geodetic reference receivers. The user's software uses the phase observable, not to smooth the range data, but as a basic data type in the user's positioning filter, whose states include along with the user's position and clock, the necessary phase biases and optionally a slowly varying zenith troposphere parameter. Tests of user positions show 8 cms RMS accuracy in the horizontal and 20 cms RMS accuracy in the vertical.

The global differential corrections computed by RTG are packaged into a 560 bit/sec message, and are made available on the open Internet via a TCP server running at JPL.

Enabling Software

RTG (Real-Time GIPSY)

RTG provides real-time estimates of the dynamic GPS orbits, and one-second GPS clocks [*Bertiger et al. 1998].* Orbit estimates are needed less frequently than the clocks due to their slower varying physical behavior. RTG contains many of the precise models contained in JPL's GIPSY OASIS II (GOA II) software. GOA II has a long history in precise orbit determination of GPS and other spacecraft equipped with GPS receivers [*Muellerschoen, 1994,1995*; *Bertiger,1994*; *Gold,1994*; *Haines,1995]*, and in precise GPS geodetic applications [*Heflin,1994*; *Argus,1995*]. Post-processing of global GPS data with GOA II routinely yields better than 10 cm GPS orbits.

Additionally, RTG has been embedded in real-time user equipment for flight on the X33 sub-orbital vehicle, and has flown on the NASA DC-8 SAR flights [*Muellerschoen, 1999*].

RTNT (Real-Time Net Transfer)

RTNT returns 5 of the 6 GPS data types: CA range, P1 and P2 ranges, and P2 phase, and either the P1 or CA phase, plus signal to noise ratios. The data is edited, smoothed, and compressed down to 21 bytes/GPS, with 17 bytes of overhead needed for time-tag, site id, navigation solution, sequence number, and status flags. For example, if a remote site tracks 10 GPS satellites, 227 bytes/sec are transmitted to a central data daemon at JPL. Additionally, the broadcast ephemeris is included in this transmission when new iode numbers are observed.

For improved reliability, the central data daemon keeps track of the sequence number of these packets from each remote site, and may request up to 3 retransmissions of missed data epochs. The central data daemon may have a twin data daemon running on another computer. The central data daemon relays all of its incoming GPS data to its twin also via socket communications. Should the twin no longer see any data flow, it will send out a request to the entire global network to request re-routing of the real-time data to itself. It would then serve as the central data daemon until the primary daemon is brought back on-line. It is also possible to chain these data daemons in order to export the real-time GPS data to any other computer on the open Internet, and also merge streams from different data daemons or additional receivers.

The remote sites minimally have a dual-frequency GPS receiver, a PC running linux operating system, and connectivity to the open Internet. RTNT currently supports the data streams from Ashtech Z-12, Turbo-Rogue, and AOA-ACT Benchmark GPS receivers. A particular data daemon running on a PC at the remote site establishes communications with the receiver through its serial port, and places the data in a revolving buffer of shared memory. A second process that is independent of receiver type, reads this shared memory and opens a socket connection to the central data daemon. The data is checked and flagged for phase breaks, and then transmitted over the socket. In addition, "soc" files are constructed which contains the data packets transmitted over the socket. These are later retrieved in batch mode to support JPL's GGN activities. Conversion routines are available from soc files to standard rinex files.

System Overview

Data Collection

Fig. 1 shows a map of the current real-time receiver network. Data returned includes dual-frequency phase measurements with a resolution of 0.02 mm, and dual-frequency range measurements with a resolution of 1 mm, the receiver's solution for its time, and broadcast ephemeris information. At JPL, these data are collected by a central data daemon that sorts the data according to time-tag, rejects duplicate transmissions, and makes requests for retransmission of missed data packets. At specified latency times of 2 and 6 seconds, all data with a common epoch is written into circular shared memory buffers. In general, the these two buffers contain the same data, however data that arrives late, such as retransmitted data, can still be included to the 6 second latency buffer. This buffer is then used by the RTG orbit process since the orbits have a slower varying physical behavior. The clocks on the other hand are less predictable, and hence use the 2 second latency buffer.

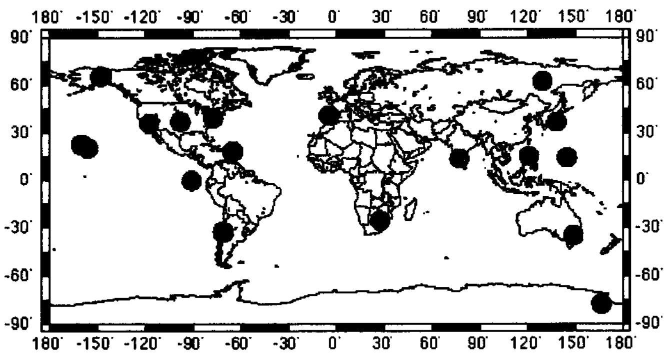

Figure 1.) Network of dual-frequency GPS reference receivers returning data to JPL in real-time. Current network consists of 4 AOA-ACT Benchmarks, 3 Turbo-Rogues, and 11 Ashtech Z-12s.

Data Latencies

Data latency is the difference between the GPS time-tag and the time the data arrives at JPL. The web page http://gipsy.jpl.nasa.gov/igdg/demo/index.html shows the current data latencies and the number of GPS satellites tracked from the real-time network for the last 60 minutes. The recurrent 15 minute spikes in some of the data latency plots, *guaz* and *gala* for instance, corresponds to the batch retrieval of the 15 minute soc files. Some of the global sites do not have sufficient bandwidth to fully support both simultaneous transmission of the real-time stream and the batch retrieval of the soc files. The batch retrieval process of the soc files is performed sequentially from a separate computer at JPL, so these brief outages in the real-time stream are staggered. Additionally evident in some of these latency plots, *madr* and *okc1* for instance, is the 5 minute meteorological data retrieval activity that also is sharing bandwidth with the real-time stream. The 0.1 second scatter in the floor of the latency plots is a consequence of an imposed 0.1 second sleep at the remote sites to minimize CPU usage on the PCs.

Orbit Determination and Clock Estimation

RTG reads the shared memory output of the central data daemon process. Orbit and troposphere estimates at the reference stations are computed once per minute by the orbit process. These estimates are then placed into another revolving buffer of shared memory so that they may be used by the clock process to compute clock solutions at 1 Hz.

Fig. 2 shows a plot of the real-time and post-processed wet-zenith troposphere estimates of the Oklahoma receiver on June 19, 2000. The post-processed troposphere estimate is obtained by point-positioning the rinex file with GOA II using precise orbits and clocks. These post-processed troposphere solutions are know to be accurate to 1 cm. The RMS difference between the real-time and post-processed "truth" troposphere estimates is 1.0 cm.

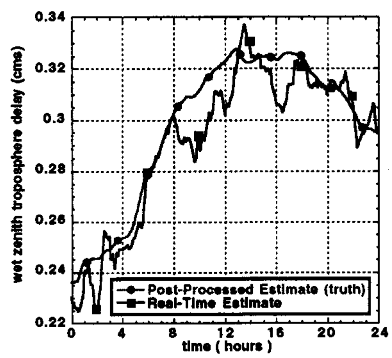

Figure 2.) Truth and the real-time wet-zenith troposphere estimates agree to 1.0 cms. (RMS)

Fig. 3 shows a plot of GPS 16 orbit error over a 3 day period, along with the number of ground receivers tracking GPS 16. This plot includes a cold-start of the orbit process with initial conditions obtained from the broadcast ephemeris. It takes about 6 hours for the orbit filter to reduce orbit errors to under 1 meter. If the orbit process is initialize with IGS predicted orbits, this settling time is around 3 hours.

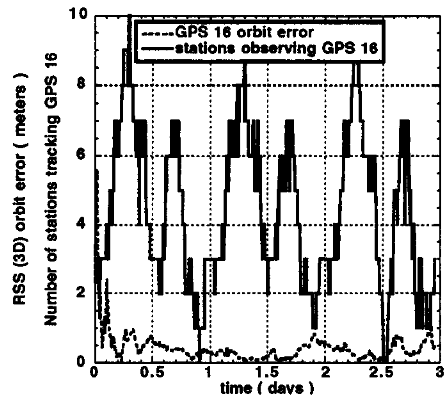

Figure 3.) Bottom line is the real-time RSS 3-D orbit errors for GPS 16 for a 3 day period. The top line is the number of reference receivers tracking GPS 16 with the current 18 station global network.

Fig. 3 also shows that when GPS 16 is poorly tracked the orbit errors are held in check due to the dynamic and predictable nature of the orbits. However they do tend increase to the meter level shortly after these periods. These outage periods are occurring mainly over Africa and the Western Indian Ocean. We anticipate that a receiver scheduled to be installed before September 2000 in Uganda, Africa will greatly reduce these holes in the GPS coverage.

The orbit process also estimates x and y polar motion parameters and their rates, along with a ut1-utc rate term. Figs. 4 and 5 show plots of the real-time polar motion estimates and the IGS rapid service combination solution for the period May 31 to June 9, 2000. For x and y polar motion, the RMS differences with the IGS solution are 0.376 and 0.378 masc., respectively.

In our initial results [*Muellerschoen, 2000*] the global GPS orbit error was about 1 meter (3D RSS of the three position components). Since then we have included and tuned stochastic dynamic partials for 3 solar-scale factors and a y-bias parameter. Also the orbit integrator now includes the effects of solid earth tides, pole tides, and ocean tides. Fig. 6 shows a plot of the 3D RSS orbit difference with the next day IGS rapid service combined orbit solution. A scheduled power outage at JPL occurred over the weekend of 10-June, and additional s/w changes were made on 12-June. The orbit process was restarted on 13-June; the orbit settling errors for this day are not shown in Fig. 6.

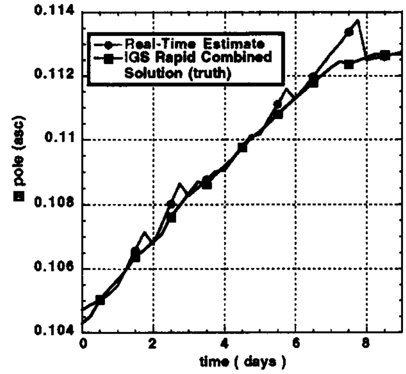

Figure 4.) IGS rapid combined solution and the real-time x pole estimates agree to 0.376 masc. (RMS)

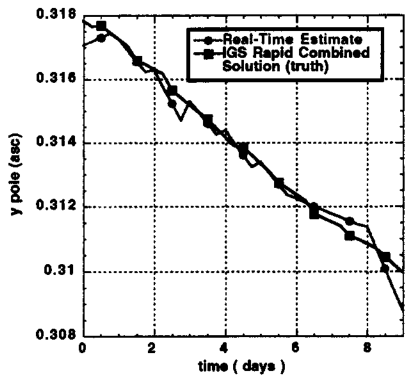

Figure 5.) IGS rapid combined solution and the real-time y pole estimates agree to 0.378 masc. (RMS)

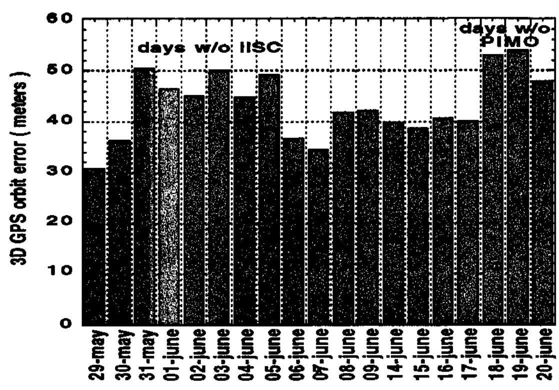

Figure 6.) RMS of the 3D orbit differences between the real-time GPS orbits and the next day IGS rapid service combined solution (truth). IISC (India) was pulled out of service on day 30-May and returned to the real-time stream on 6-June. PIMO (Philippines) experienced a network failure on 18-June due to a lighting strike.

Fig. 6 shows that when all 18 of global real-time sites are transmitting, the 3D GPS orbit error is 30-40 cms.

Global Differential Correctors

Orbit and clock estimates are differenced with the broadcast ephemeris and broadcast clock. Corrections to these broadcast elements are packaged into a 560 bit message. Each message contains 4 orbit solutions, 4 meter-level clocks, and 32 cm-level clock corrections. The total clock correction is the sum of meter-level clock and the cm-level clock corrections. It requires 8 seconds for the user to initialize all 32 prn orbit and clock differential corrections. The resolution of the clock corrections is 1.5625 cms. This is 8 times smaller than the resolution of the WAAS corrections. The orbit correction resolution is 6.25 cms which is the same as the WAAS resolution. iode ephemeris changes are held 2 minutes after new iodes are observed. This gives the user sufficient time to also accumulate the newest ephemeris message.

The global differential corrections are made available currently over the open Internet via a TCP server running at JPL. Code to obtain the real-time global differential corrections is available at:

ftp://sideshow.jpl.nasa.gov/pub/rjm/jplGdGPS/

Note however that both the server IP and port number may change as the system further develops.

User Positioning Tests

To test the accuracy of the global differential GPS correctors, we kinematically position a stationary GPS receiver at a known location. The same RTG s/w used on the DC-8 flights [*Muellerschoen, Bertiger 1999*] is used with the global differential GPS correctors obtained through a socket connection from JPL's global differential TCP server.

A plot of kinematic positioning of a static user is shown at http://gipsy.jpl.nasa.gov/igdg/demo/index.html. In this live demo, a GPS receiver on JPL's Mesa uses RTNT to transmit its data to a laptop computer at the author's desk, where it is kinamatically positioned in real-time using the global differential corrections. The resulting solutions are ftp'ed to the web display every 30 minutes.

Figs. 7 and 8 show the horizontal RMS errors of the demo receiver at JPL's Mesa over 6 hour periods. Fig. 9 shows the vertical errors. The gap in the middle is related to the previous mentioned scheduled power outage at JPL. The RMS error over all these 6 hour periods is 8 cms in East, 7 cms in North, and 21 cms in Vertical.

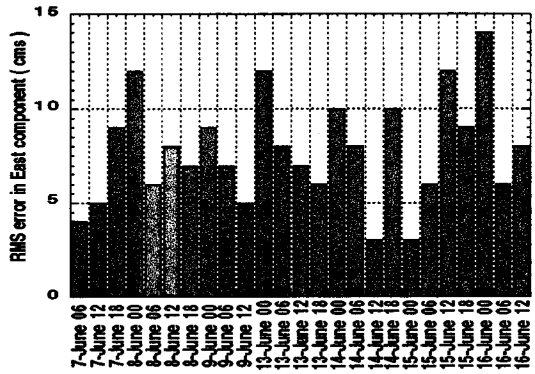

Figure 7.) East error of user positioning.

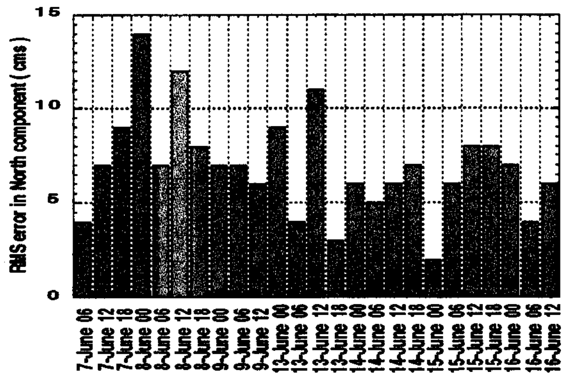

Figure 8.) North error of user positioning.

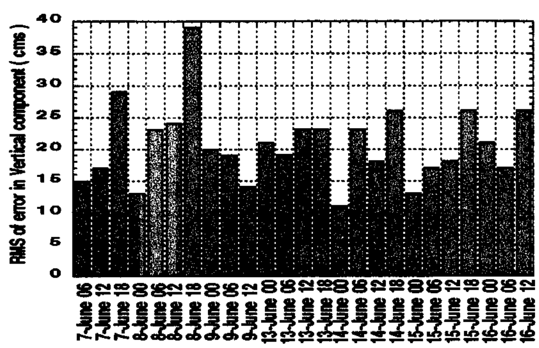

Figure 9.) Vertical error of user positioning.

To demonstrate the effectiveness of separation of clock and orbit error with the state-space approach, we ran the 1 Hz. clock process without the Goldstone, California reference site and kinematically positioned JPL's Mesa demo receiver. Figs. 10 and 11 demonstrate the horizontal positioning of JPL's Mesa demo receiver with and without

Goldstone in the clock process. Fig. 12 shows the vertical errors. Without the Goldstone site, the nearest reference receiver in the real-time network is in Oklahoma. The overall RMS error without Goldstone in the 1 Hz. clock process is 7 cms in East, 8 cms in North, and 20 cms in Vertical. With Goldstone in the clock process, the overall RMS for the same period is 8 cms in East, 9 cms in North, and 23 cms in Vertical. The reason for this contradiction appears to be several meter multipath at Goldstone for low-elevation (< 25 degrees) data. This problem has since been corrected, and only Goldstone data above 25 degrees is processed by both the orbit and clock processes. Regardless of this contradiction, the results demonstrate that it is not necessary to be near a reference receiver to obtain the same accuracy.

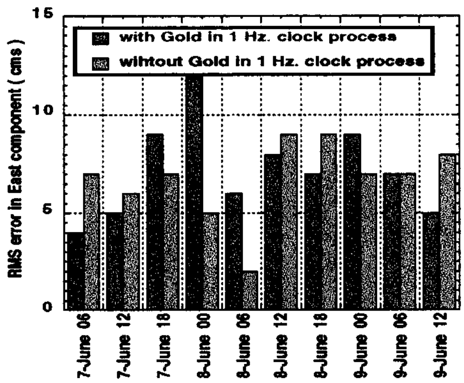

Figure 10.) East error of user positioning with and without Goldstone, CA reference receiver in the 1 Hz. clock process.

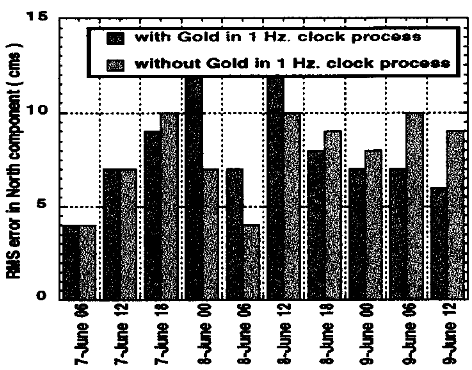

Figure 11.) North error of user positioning with and without Goldstone, CA reference receiver in the 1 Hz. clock process.

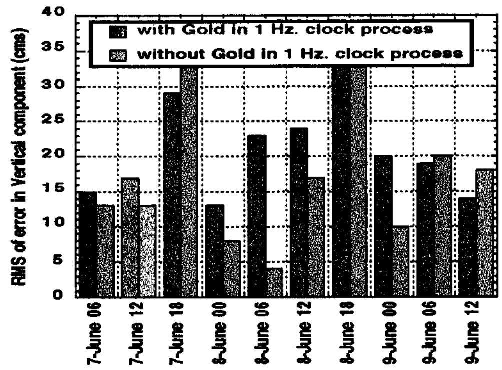

Figure 12.) Vertical error of user positioning with and without Goldstone, CA reference receiver in the 1 Hz. clock process.

Summary

The open Internet is a reliable choice to return GPS data for a state-space dual-frequency global differential system. Results show 8 cms horizontal accuracy and 20 cms vertical accuracy. When all 18 of the global real-time sites are transmitting, the 3D GPS orbit error is 30-40 cms. As more stations come on-line, the GPS orbit errors will be reduced, and the overall system more robust through redundancy of the network.

Acknowledgments

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